Too Hot to Handle

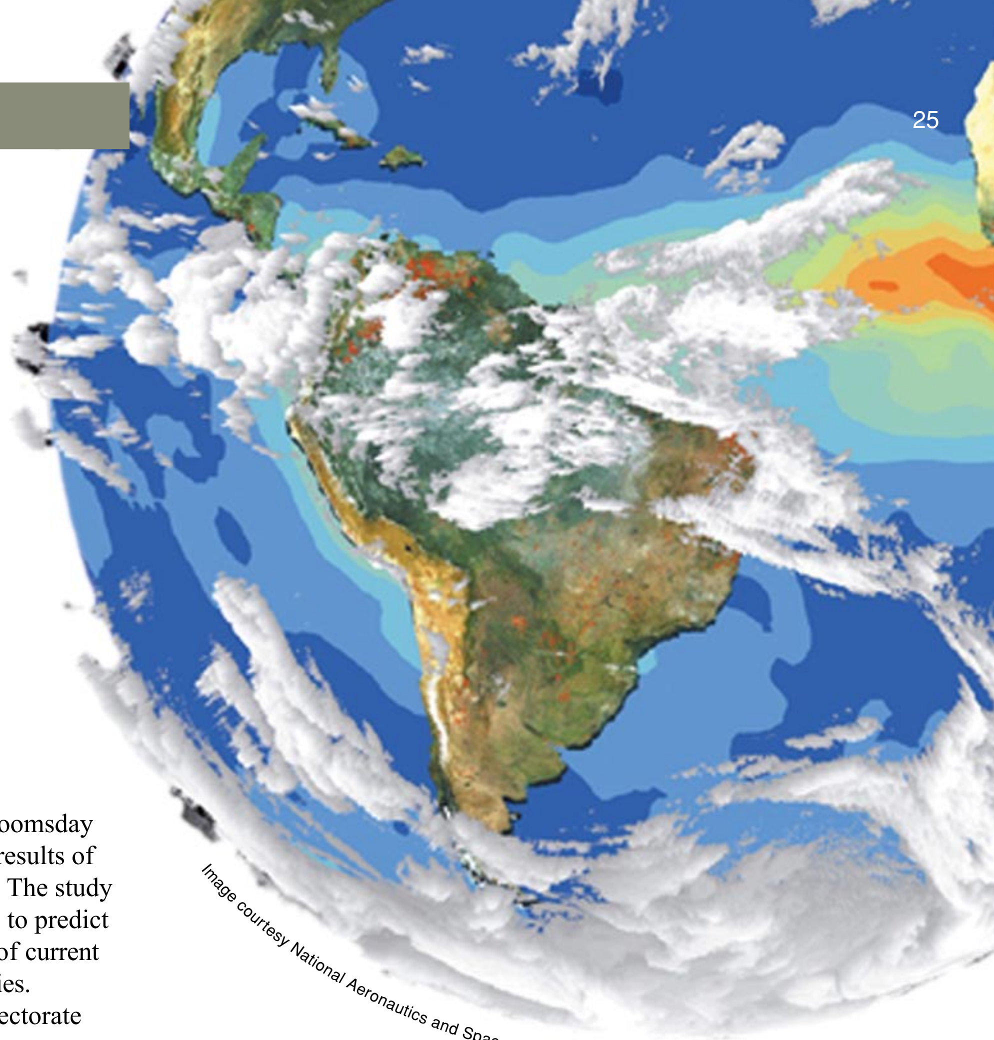


Image courtesy National Aeronautics and Space Administration.

IF humans deplete the world's supply of fossil fuels in the next 300 years as they are on track to do, they will be faced with many more challenges than just finding alternative energy sources.

According to Livermore physicist Govindasamy Bala, humans inhabiting polar regions would have to figure out new methods of subsistence as their ice and tundra landscapes turn into boreal forests as a result of temperatures spiking more than 20°C. Even more striking, residents of certain islands that rise only a few meters above sea level would be looking for a new home entirely, as their communities slowly disappear beneath a rising sea.

Although these scenarios sound like material for a doomsday plot straight out of Hollywood, they do, in fact, reflect results of computer simulations recently conducted at Livermore. The study is the first to combine climate and carbon-cycle models to predict out to 300 years the long-term, global climate effects of current and future energy usage and resource management policies.

Bala's team within the Energy and Environment Directorate also includes physicists Arthur Mirin and Michael Wickett. Physicist Ken Caldeira, formerly a Laboratory employee, collaborates from the Carnegie Institution. The study, funded by the Laboratory Directed Research and Development Program, supports the Department of Energy's (DOE's) mission priorities in energy and environment. This work is one of Livermore's programs that contribute to the scientific and technological basis for secure, sustainable, and clean energy resources.

How Did We Get Here from There?

When fossil fuels are burned to create the energy we need to run our cars, heat our homes, and power industry, they emit carbon dioxide—a heat-trapping gas also commonly known as greenhouse gas. The scientific community has reached near consensus that the accumulation of such gases in Earth's atmosphere is causing a global warming trend. How soon we will see, and be affected by, the consequences of this gradual warming continues to be a source of debate.

Climate data show some warming has already occurred. "Over the 20th century, the average global temperature has increased more than half a degree," says Bala. What many climate researchers would like to know is where the trend is going and how fast it is getting there.

To predict the outcomes of different energy- and resource-usage scenarios, scientists depend on computer models that are of increasingly higher resolution, include better physics models, and are validated with observations. Bala underscores the value of Livermore's massively parallel computing capabilities in pushing this research ahead. "These simulations require very high-capability computing," says Bala, whose team has used nearly every supercomputing machine in the DOE complex to run several climate codes. Beyond running simulations to study scenarios, the Laboratory plays a broader role in climate research for DOE. Livermore's Program for Climate Model Diagnosis and Intercomparison develops methods and tools for diagnosing, validating, and comparing the global climate models used for predicting climate change.

We're Getting Warmer

Climate model simulations performed in the past have been limited to predicting the effects of this trend out only 100 years or so. Bala's study included data that looked forward to 2300.

The resulting predictions, which are intended to give a big-picture view, showed an average increase in global temperature of 8°C by 2300 and implied that the Greenland ice sheet could completely melt, triggering a sea level rise of 7 meters over the next several centuries. The simulations also pointed to a 20°C warming over the Arctic by 2300. "What is alarming about this recent study is that severe changes to the distribution of terrestrial vegetation can also occur much more rapidly than we previously thought," says Bala.

Of even more concern, he says, is that the team was conservative with some of the input used in the simulation code. "This model did not consider changing land use such as deforestation and the expansion of metropolitan areas," he says. "These factors would have an even greater effect on the global temperature if they were included."

Bala's team couples both climate and carbon-cycle simulations to model climate change. This coupling has produced data that Bala believes are more accurate than past studies, which have relied just on climate models. "The coupling realistically represents the interaction between climate and the carbon cycle, and our model simulated atmospheric carbon dioxide concentrations and surface mean temperature changes that are in line with observations over the 20th century," says Bala.

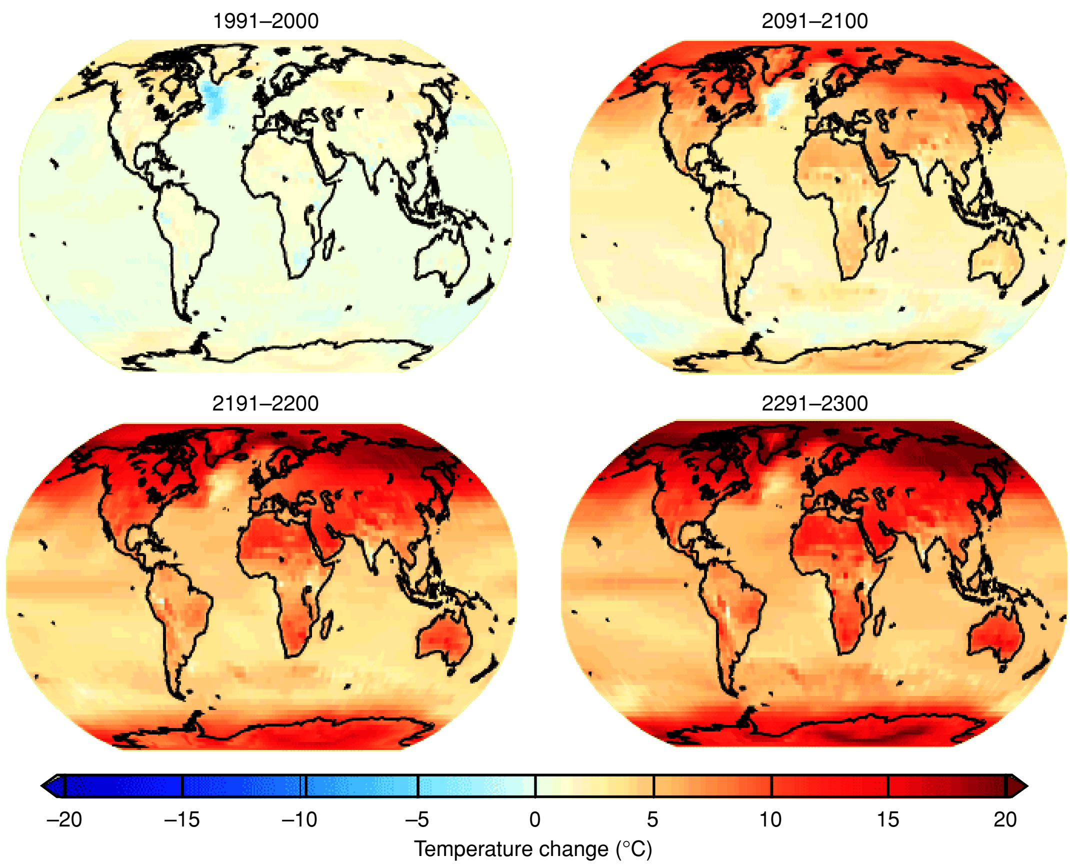
Carbon Sinks and Acid Oceans

Atmospheric carbon dioxide emissions from the burning of fossil fuels affect the carbon content of both terrestrial and oceanic systems—and both of those carbon reservoirs affect climate and vice versa. The flow of carbon dioxide through the atmosphere and the terrestrial and marine ecosystems is referred to as the carbon cycle. Bala's model predicts that Earth's level of atmospheric carbon dioxide will nearly quadruple by the year 2300.

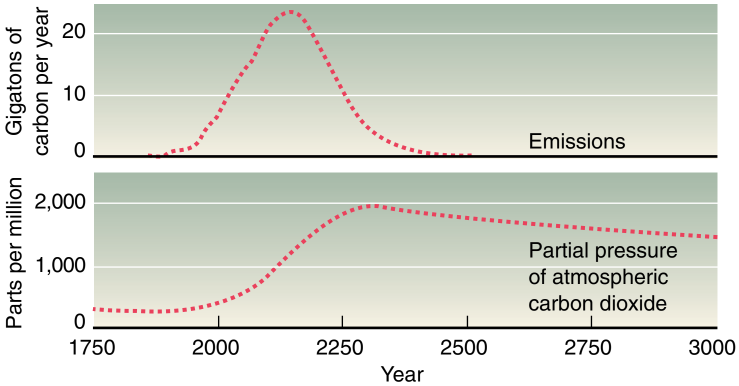
Carbon dioxide, however, does not remain indefinitely in the atmosphere. It is taken up by terrestrial carbon sinks—living biomass and soils—and, in large part, the oceans. Indeed, about 80 percent of carbon dioxide eventually ends up in the oceans. Bala's simulations show a significant increase in the acidity of the oceans when fossil-fuel stores are depleted. "This phenomena will occur even if climate change does not happen," says Bala.

The acidification of the oceans is expected to be quite damaging to marine life. And, in typical ecosystem fashion, the destruction of certain marine organisms is likely to feed back into the climate cycle. In question is the fate of marine organisms, such as corals, that are made of calcium carbonate shells and skeletal materials. These organisms normally act to regulate ocean chemistry and, in turn, the ocean's ability to absorb carbon dioxide from the atmosphere. Observations have already shown that even a few degrees of ocean warming threaten the existence of some coral reefs. Scientists predict that the destruction of these coral systems would hamper the ocean's ability to adequately absorb atmospheric carbon dioxide.

Bala's simulations predict that eventually the ability of oceans to absorb carbon dioxide would decline, and about 45 percent of the emitted carbon dioxide would remain in the atmosphere. The



Computer modeling data of the global surface-temperature change over the next 300 years indicate the Arctic will be warmer by 20°C in 2300. All plots are referenced to preindustrial times (1891–1900).



Determining how large the concentrations of atmospheric carbon dioxide will be in the future depends on how much fossil fuel is emitted. The top curve shows the emission rate of carbon dioxide and supposes all the estimated conventional fossil-fuel resources will be depleted by the year 2500. The bottom curve shows the resulting carbon dioxide concentrations up to year 3000. Ocean absorption of carbon dioxide is taken into account, but climate and land carbon changes are not.

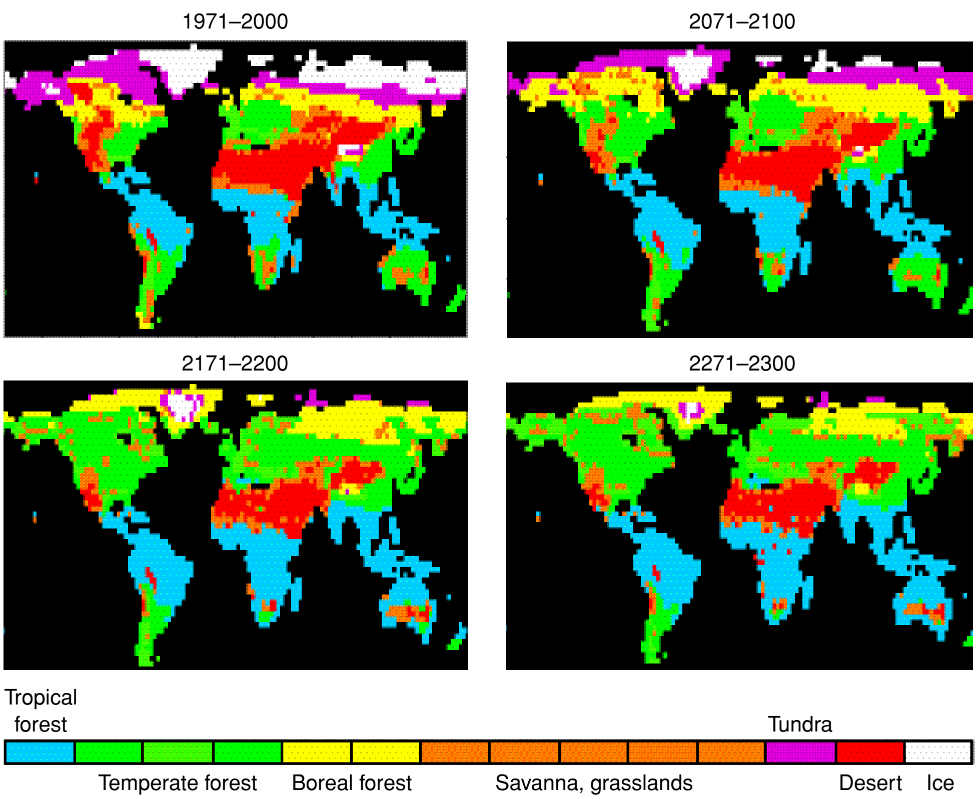
model also shows that the warming trend would reduce terrestrial uptake and the ability of soils to retain carbon dioxide. Moreover, the warmer climate would change the distribution of terrestrial vegetation on a large scale. For example, tropical and temperate forests would expand, with Arctic tundra transforming into boreal forests by 2200.

No Time to Lose

If this study were only a cautionary tale, it would be enough to make individuals and policy makers alike take pause and commit to reversing the trend. However, as Bala points out, it is now evident that damage has already been done. "We have what is called 'committed warming,' which is already set in motion," says Bala. "No matter what we do—even if we completely stop burning fossil fuels today—we are committed to further increases in global temperature. Although a consensus does not yet exist on the amount of committed warming, a recent study estimates that it could be about 0.6°C. Our present trajectory is risking severe environmental damage that could last many hundreds of years."

Computer simulations using integrated models offer a glimpse into the future and an opportunity to mitigate damage yet to come. "We are just in the beginning of this integrated assessment," says Bala. "Many challenges are ahead."

—*Maurina S. Sherman*



Simulations of the changes in global dominant vegetation types show that northern ice caps will begin vanishing this century and tundra regions will disappear within 200 to 300 years.

Key Words: carbon cycle, carbon dioxide emissions, carbon sink, climate modeling, deforestation, fossil-fuel depletion, global climate change, global warming, greenhouse gases, land use, oceanic acidity, vegetation change.

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